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Thermodynamic aspects of renewables and sustainable development

Ibrahim Dincer *, Marc A. Rosen

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ont., Canada L1H 7L7

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Abstract

Achieving sustainable solutions to today's energy and environmental problems requires long-term planning and actions. Energy issues are particularly prevalent at present and renewable energy resources appear to provide one component of an effective sustainable solution. An understanding of the thermodynamic aspects of sustainable development can help in taking sustainable actions regarding energy. Discussed in this article are possible future energy-utilization patterns and related environmental impacts, potential solutions to current environmental problems, renewable energy technologies and their relations to sustainable development, and how the principles of thermodynamics via exergy can be beneficially used to evaluate energy systems and technologies as well as environmental impact. Throughout the article, current and future perspectives regarding thermodynamics and sustainable development are considered. The results will likely be useful to scientists and engineers as well as decision and policy makers.

Contents

* Corresponding author. Tel.: +1-905-721-3111; fax: +1-905-721-3140.
E-mail address: ibrahim.dincer@uoit.ca (I. Dincer).

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1. Introduction

Energy is the driver of technology, life and society. Energy resources help in creating wealth and improving living standards for individuals and societies. Furthermore, development that is sustainable requires, among other factors, access to energy resources. Energy, consequently, is a key consideration in discussions of sustainable development.

Energy use is very much governed by thermodynamic principles and, therefore, an understanding of thermodynamic aspects of energy can help us understand pathways to sustainable development [1].

Sustainable development has been defined in many ways, including "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. Many factors affect achieving sustainable development.

A secure supply of energy resources is generally necessary but not sufficient for societal development. Sustainable societal development, however, requires a sustainable supply of energy resources, i.e. a secure supply that is readily and sustainably available in the long term at reasonable cost and that can be utilized for all required tasks without causing negative societal impacts [3–6]. Effective and efficient utilization of energy resources can also contribute to sustainable development.

Renewable energy resources are often sustainable. Most energy supplies on earth derive from the sun, which continually warms us and supports plant growth via photosynthesis. Solar energy heats the land and sea differentially and so causes winds and consequently waves. Solar energy also drives evaporation, which leads to rain and in turn hydropower. Tides are the result of the gravitational pull of the moon and sun and geothermal heat is the result of radioactive decay within the earth.

Many diverse energy-related problems and challenges are faced today. Some examples follow:

- Growing energy demand. The annual population growth rate is currently around 2% worldwide and higher in many countries. By 2050, world population is expected to double and economic development is expected to continue, improving standards of living in many countries. Consequently, global demand for energy services is expected to increase by up to 10 times by 2050 and primary-energy demand by 1.5–3 times [7–9].
- Excessive dependence on specific energy forms. Society is extremely dependent on access to specific types of energy currencies. The effect of the multi-day blackout of 2003 in Ontario and several northeastern US states illustrated the dependency on electricity supply, as access was lost or curtailed to computers, elevators, air conditioners, lights and health care. Developed societies would come to a virtual standstill without energy resources.
- Energy-related environmental impacts. Continued degradation of the environment by people, most agree, will have a negative impact on the future, and energy processes lead to many environmental problems, including global climate change, acid precipitation, stratospheric ozone depletion, emissions of a wide range of pollutants including radioactive and toxic substances, and loss of forests and arable land.
- The dominance of non-sustainable and non-renewable energy resources. Limited use is made today of renewable energy resources and corresponding technologies, even though such resources and technologies provides a potential solution to current and future energy-resource shortages. By considering engineering practicality, reliability, applicability, economics and public acceptability, appropriate uses for sustainable and renewable energy resources can be found. Of course, financial and other resources should not always be dedicated to renewable energy resources [9], as excessively extravagant or impractical plans are often best avoided.
- Energy pricing that does not reflect actual costs. Many energy-resource prices have increased over the last couple decades, in part to account for environmental costs, yet many suggest that energy prices still do not reflect actual societal costs.
- Global disparity in energy use. Wealthy industrialized economies which contain 25% of the world's population use 75% of the world's energy supply [9].

These and other energy-related issues need to be resolved if humanity and society are to develop sustainably in the future. The main objective of this article, consequently, is to help in resolving these issues and thus contribute to the goal of achieving sustainable development. Renewable energy resources appear to provide one component of an effective sustainable solution, and can contribute over the long term to achieving sustainable solutions to today's energy problems. In addition, an understanding of the thermodynamic aspects of sustainable development can help in taking sustainable actions regarding energy.

In this article, possible future energy-utilization patterns and related environmental impacts, potential solutions to current environmental problems, and renewable energy technologies and their relations to sustainable development are described. In addition, we consider the use of thermodynamics principles via exergy to evaluate energy systems and environmental impact, so as to explain the benefits of addressing environmental impacts using thermodynamic principles. Throughout, practical cases and current and future perspectives regarding thermodynamics and sustainable development are considered and an illustrative example is presented.

2. Exergy and exergy analysis

Exergy analysis is a technique that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems [10].

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Rather exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

Exergy analysis is useful for improving the efficiency of energy-resource use, for it quantifies the locations, types and magnitudes of wastes and losses. In general, more meaningful efficiencies are evaluated with exergy analysis rather than energy analysis, since exergy efficiencies are always a measure of how nearly the efficiency of a process approaches the ideal. Therefore, exergy analysis identifies accurately the margin available to design more efficient energy systems by reducing inefficiencies. Many engineers and scientists suggest that thermodynamic performance is best evaluated using exergy analysis because it provides more insights and is more useful in efficiency-improvement efforts than energy analysis.

For exergy analysis, the characteristics of a reference environment must be specified. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment. The results of exergy analyses, consequently, are relative to the specified reference environment, which in most applications is modeled after the actual local environment. The exergy of a system is zero when it is in equilibrium with the reference environment. This tie between exergy and the environment has implications regarding environmental impact that are discussed subsequently.

2.1. Energy and exergy balances

Energy and exergy balances for an unsteady-flow process in a system during a finite time interval can be written as:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{1}$$

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \tag{2}$$

The above equations demonstrate an important difference between energy and exergy: energy is conserved, while exergy is consumed due to irreversibilities. Exergy indicates the quality of energy which, in any real process, is not conserved, but rather is in part destroyed or lost. Eqs. (1) and (2) can be formulated as:

$$\sum_{\text{in}}(h + \text{ke} + \text{pe})_{\text{in}} m_{\text{in}} - \sum_{\text{ex}}(h + \text{ke} + \text{pe})_{\text{ex}} m_{\text{ex}} + \sum_r Q_r - W = 0 \tag{3}$$

$$\sum_{\text{in}} \varepsilon_{\text{in}} m_{\text{in}} - \sum_{\text{ex}} \varepsilon_{\text{ex}} m_{\text{ex}} + \sum_r E^Q - E^W - I = 0 \tag{4}$$

where m_{in} and m_{ex} denote mass input across port "in" and mass exiting across port "ex", respectively; Q_r denotes the amount of heat transfer into the system across region r on the system boundary; E^Q is the exergy transfer associated with Q_r; W is the work (including shaft work, electricity, etc.) transferred out of the system; E^W is the exergy transfer associated with W; I is the system exergy consumption; and h, ke, pe, and ϵ denote the specific values of enthalpy, kinetic energy, potential energy, and exergy, respectively. Note that the exergy consumption I is greater than zero for an irreversible process and equal to zero for a reversible process.

Since $m_{\text{in}} = m_{\text{ex}} = 0$, for a closed system, Eqs. (3) and (4) are simplified to:

$$\sum_r Q_r - W = 0 \tag{5}$$

$$\sum_r E^Q - E^W - I = 0 \tag{6}$$

2.2. Basic quantities for exergy analysis

Here, we discuss some basic quantities and mathematical relations related to exergy.

Exergy of a flowing stream of matter: Consider a flowing stream of matter at temperature T, pressure P, chemical composition μ_j of species j, mass m, specific enthalpy h, specific entropy s, and mass fraction x_j of species j. A conceptual

environment is considered in an equilibrium state with intensive properties at T_0, P_0 and μ_{j00}. The environment is taken to be large enough that its intensive properties are negligibly affected by any interactions with the system.

With the above considerations, the specific exergy of a flowing stream of matter can be expressed as:

$$\varepsilon = [\mathrm{ke} + \mathrm{pe} + (h - h_0) - T_0(s - s_0)] + \left[\sum_j (\mu_{j0} - \mu_{j00})x_j\right] \tag{7}$$

Note that the above equation can be separated into physical and chemical components. If $\mathrm{ke} = 0$ and $\mathrm{pe} = 0$, the physical exergy $[(h - h_0) - T_0(s - s_0)]$ is the maximum available work extracted from a flowing stream as it is brought to the environmental state. The chemical exergy $[\sum_j (\mu_{j0} - \mu_{j00})x_j]$ is the maximum available work extracted from the stream as it is brought from the environmental state to the dead state.

Exergy of heat: The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at constant temperature T_r is:

$$E^Q = \left(1 - \frac{T_0}{T_r}\right)Q_r \tag{8}$$

Exergy of work: The exergy associated with work is:

$$E^W = W \tag{9}$$

Chemical exergy: The evaluation of chemical exergy is detailed in numerous books. One of the most common mass flows is hydrocarbon fuel at near-ambient conditions, for which the first term in the square brackets in Eq. (7) is approximately zero, and the specific exergy reduces to chemical exergy, which can be written as

$$\varepsilon_\mathrm{f} = \gamma_\mathrm{f} H_\mathrm{f} \tag{10}$$

Here, γ_f denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy (last term in square brackets in Eq. (7)) to the fuel higher heating value H_f. Table 1 shows typical values of H_f, ε_f, and γ_f for the fuels encountered in the present study. Usually, the specific chemical exergy ε_f of a fuel at T_0 and P_0 is approximately equal to higher heating value H_f.

Table 1
Properties of selected fuels (for a reference environment temperature of 25 °C, the pressure of 1 atm and chemical composition as defined in the text)

Fuel	H_f (kJ/kg)	Chemical exergy (kJ/kg)	γ_f
Gasoline	47 849	47 394	0.99
Natural gas	55 448	51 702	0.93
Fuel oil	47 405	47 101	0.99

Adapted from Reistad [23].

Exergy consumption: The amount of exergy consumed due to irreversibilities during a process is:

$$I = T_0 S_{\mathrm{gen}} \tag{11}$$

The reference environment: Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, is a sink or source for heat and materials, and experiences only internally reversible processes in which its intensive properties (i.e. temperature T_0, pressure P_0 and chemical potentials μ_{j00} for each of the j components) remains constant. Often, Gaggioli and Petit's model [24] is used as a reference environment in which $T_0 = 10\ ^{\circ}\mathrm{C}$, $P_0 = 1$ atm, and the chemical composition is taken to be air saturated with water vapor, and the following condensed phases are used at 25 °C and 1 atm: water (H_2O), gypsum ($CaSO_4 \cdot 2H_2O$), and limestone ($CaCO_3$). It is noted that, following Gaggioli and Petit [24], gypsum and limestone are taken to be part of the reference environment so as to provide nonreactive, dead-state chemical forms for the elements sulphur and calcium.

2.3. Energy and exergy efficiencies for principal types of processes

The expressions of energy (η) and exergy (ψ) efficiencies for the principal types of processes considered in the present study are based on the following definitions:

$$\eta = (\text{energy in products}/\text{total energy input}) \tag{12}$$

$$\psi = (\text{exergy in products}/\text{total exergy input}) \tag{13}$$

Here, exergy efficiencies can often be written as a function of the corresponding energy efficiencies by assuming the energy grade function γ_{f} to be unity, which is commonly valid for many hydrocarbon fuels (e.g., kerosene, gasoline, diesel and natural gas).

Note that the exergy efficiency frequently gives a finer understanding of performance than the energy efficiency. In calculating the energy efficiency, the same weight is assigned to energy whether it becomes shaft work or a stream of low temperature fluid. Also, it centers attention on reducing "losses" to improve efficiency. The exergy efficiency weights energy flows by accounting for each in terms of availability. It stresses that both losses and internal irreversibilities need to be dealt with to improve performance. In many cases, it is the irreversibilities that are more significant and the more difficult to deal with.

- *Heating*: Electric and fossil fuel heating processes are taken to generate product heat Q_{p} at a constant temperature T_{p}, either from electrical energy W_{e} or fuel mass m_{f}. The efficiencies for electrical heating are

$$\eta_{\mathrm{h,e}} = Q_{\mathrm{p}}/W_{\mathrm{e}} \tag{14}$$

$$\psi_{\mathrm{h,e}} = E^{Q_{\mathrm{p}}}/E^{W_{\mathrm{e}}} = ((1 - T_0/T_{\mathrm{p}})Q_{\mathrm{p}})/(W_{\mathrm{e}}) \quad \text{and}$$

$$\psi_{\mathrm{h,e}} = (1 - T_0/T_{\mathrm{p}})\eta_{\mathrm{h,e}} \tag{15}$$

For fuel heating, these efficiencies are

$$\eta_{h,f} = Q_p/m_f H_f \tag{16}$$

$$\psi_{h,f} = E^{Q_p}/m_f \varepsilon_f \text{ and } \psi_{h,f} = ((1 - T_0/T_p)Q_p)/(m_f \gamma_f H_f) \cong (1 - T_0/T_p)\eta_{h,f} \tag{17}$$

where double subscripts indicate the processes in which the quantity represented by the first subscript is produced by the quantity represented by the second; e.g., the double subscript h,e means heating with electricity.

- *Cooling*: The efficiencies for electric cooling are

$$\eta_{c,e} = Q_p/W_e \tag{18}$$

$$\psi_{c,e} = E^{Q_p}/E^{W_e} = ((1 - T_0/T_p)Q_p)/(W_e) \quad \text{and} \quad \psi_{c,e} = (1 - T_0/T_p)\eta_{c,e} \tag{19}$$

- *Work production*: Electric and fossil-fuel work production processes produces shaft work W. The efficiencies for shaft work production from electricity are

$$\eta_{m,e} = W/W_e \tag{20}$$

$$\psi_{m,e} = E^{W}/E^{W_e} = W/W_e = \eta_{m,e} \tag{21}$$

For fuel, these efficiencies are

$$\eta_{m,f} = W/m_f H_f \tag{22}$$

$$\psi_f = E^{W}/m_f \varepsilon_f = W/m_f \gamma_f H_f \cong \eta_{m,f} \tag{23}$$

- *Electricity generation*: The efficiencies for electricity generation from fossil fuel are

$$\eta_{e,f} = W_e/m_f H_f \tag{24}$$

$$\psi_{e,f} = E^{W_e}/m_f \varepsilon_f = W_e/m_f \gamma_f H_f \cong \eta_{e,f} \tag{25}$$

Therefore, the exergy efficiencies for electricity generation process can be taken as equivalent to the corresponding energy efficiencies.

- *Kinetic energy production*: The efficiencies for the fossil fuel-driven kinetic energy production processes, which produces a change in kinetic energy Δke in a stream of matter m_s, are as follows:

$$\eta_{ke,f} = m_s \Delta ke_s/m_f H_f \tag{26}$$

$$\psi_{ke,f} = m_s \Delta ke_s/m_f \varepsilon_f = m_s \Delta ke_s/m_f \gamma_f H_f \cong \eta_{ke,f} \tag{27}$$

Recently, Dincer et al. [25] have applied the above methodology to Saudi Arabia's transportation sector and determined how efficiently resources are used in its

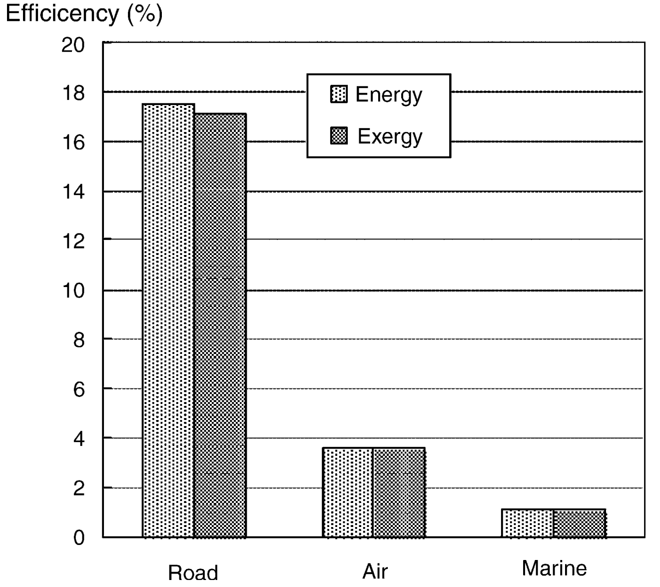

Fig. 1. Overall energy and exergy efficiencies of the subsectors of transportation sector in Saudi Arabia for the year 2000.

three main subsectors (marine, road and air) as the results are shown in Fig. 1 where it is seen that the road subsector appears to be the most energy and exergy efficient. This is due to the fuel type used and the performance of the carrier.

3. Energy, the environment and sustainable development

Sustainable development requires a sustainable supply of clean and affordable energy resources that do not cause negative societal impacts [10–14]. Supplies of such energy resources as fossil fuels and uranium are finite. Energy sources such as sunlight, wind and falling water are generally considered renewable and, therefore, sustainable over the relatively long term. Wastes and biomass fuels are also usually viewed as sustainable energy sources. Wastes are convertible to useful energy forms through such technologies as waste-to-energy incineration facilities.

Much environmental impact is associated with energy-resource utilization. Ideally, a society seeking sustainable development utilizes only energy resources that release no or minimal emissions to the environment and thus cause no or little environmental impact. However, since all energy resources lead to some environmental impact, increased efficiency can somewhat alleviate the concerns regarding environmental emissions and their negative impacts. For the same services or products, less resource utilization and pollution is normally associated with increased efficiency.

Sustainability often leads local and national authorities to incorporate environmental considerations into energy planning. The need to satisfy basic human needs and aspirations, combined with increasing world population, will make the need for successful implementation of sustainable development increasingly apparent. Various criteria that are essential to achieving sustainable development in a society follow [10]:

- information about and public awareness of the benefits of sustainability investments,
- environmental education and training,
- appropriate energy strategies,
- the availability of renewable energy sources and cleaner technologies,
- a reasonable supply of financing, and
- monitoring and evaluation tools.

3.1. Environmental concerns and sustainable development

Environmental concerns are significantly linked to sustainable development. Activities which continually degrade the environment are not sustainable. For example, the cumulative impact on the environment of such activities often leads over time to a variety of health, ecological and other problems.

Clearly, a strong relation exists between efficiency and environmental impact since, for the same services or products, less resource utilization and pollution is normally associated with increased efficiency [10].

Improved energy efficiency leads to reduced energy losses. Most efficiency improvements produce direct environmental benefits in two ways. First, operating energy input requirements are reduced per unit output, and pollutants generated are correspondingly reduced. Second, consideration of the entire life cycle for energy resources and technologies suggests that improved efficiency reduces environmental impact during most stages of the life cycle.

In recent years, the increased acknowledgment of humankind's interdependence with the environment has been embraced in the concept of sustainable development. With energy constituting a basic necessity for maintaining and improving standards of living throughout the world, the widespread use of fossil fuels may have impacted the planet in ways far more significant than first thought. In addition to the manageable impacts of mining and drilling for fossil fuels and discharging wastes from processing and refining operations, the "greenhouse" gases created by burning these fuels is regarded as a major contributor to a global warming threat. Global warming and large-scale climate change have implications for food chain disruption, flooding and severe weather events.

Use of renewable energy sources can help reduce environmental damage and achieve sustainability. Energy from these sources currently accounts for only about 10% of US total electricity consumption. Renewables, which essentially do not consume fuel, contribute to global warming, or generate substantial waste [7].

3.2. Attributes, benefits and drawbacks of renewables

The attributes of renewable energy technologies (e.g., modularity, flexibility, low operating costs) differ considerably from those for traditional, fossil fuel-based energy technologies (e.g., large capital investments, long implementation lead times, operating cost uncertainties regarding future fuel costs). Renewable energy technologies can provide cost-effective and environmentally beneficial alternatives to conventional energy systems. Some of the benefits that make energy conversion systems based on renewable energy attractive follow [7,13]:

- They are relatively independent of the cost of oil and other fossil fuels, which are projected to rise significantly over time. Thus, cost estimates can be made reliably for them for renewable energy systems and they can help reduce the depletion of the world's non-renewable energy resources.
- Implementation is relatively straightforward.
- They normally do not cause excessive environmental degradation and so can help resolve major environmental problems. Widespread use of renewable energy systems would certainly reduce pollution levels.
- They are often advantageous in developing countries. In fact, the market demand for renewable energy technologies in developing nations will likely grow as they seek a better standard of living.

Renewable energy resources have some characteristics that lead to problematic but often solvable technical and economic challenges:

- generally diffuse,
- not fully accessible,
- sometimes intermittent, and
- regionally variable.

The overall benefits of renewable energy technologies are often not well understood, leading to such technologies often being assessed as less cost-effective than traditional technologies. For renewable energy technologies to be assessed comprehensively, all of their benefits must be considered. For example, many renewable energy technologies can provide, with short lead times, small incremental capacity additions to existing energy systems. Such power generation units usually provide more flexibility in incremental supply than large devices like nuclear power stations.

3.3. Renewables and sustainable development

Renewable energy has an important role to play in meeting future energy needs in both rural and urban areas [14]. The development and utilization or renewable energy should be given a high priority, especially in the light of increased awareness of the adverse environmental impacts of fossil-based generation. The need for

sustainable energy development is increasing rapidly in the world. Widespread use of renewable energy is important for achieving sustainability in the energy sectors in both developing and industrialized countries.

Renewable energy resources and technologies are a key component of sustainable development for three main reasons [12]:

- They generally cause less environmental impact than other energy sources. The variety of renewable energy resources provides a flexible array of options for their use.
- They cannot be depleted. If used carefully in appropriate applications, renewable energy resources can provide a reliable and sustainable supply of energy almost indefinitely. In contrast, fossil fuel and uranium resources are diminished by extraction and consumption.
- They favor system decentralization and local solutions that are somewhat independent of the national network, thus enhancing the flexibility of the system and providing economic benefits to small isolated populations. Also, the small scale of the equipment often reduces the time required from initial design to operation, providing greater adaptability in responding to unpredictable growth and/or changes in energy demand.

Not all renewable energy resources are inherently clean in that they cause no burden on the environment in terms of waste emissions, resource extraction or other environmental disruptions. Nevertheless, use of renewable energy resources almost certainly can provide a cleaner and more sustainable energy system than increased controls on conventional energy systems.

To seize the opportunities, a country should establish a renewable energy market and gradually build up the experience with the technologies. The barriers and constraints to the diffusion of renewables should be removed. The legal, administrative and financing infrastructure should be established to facilitate planning and application of renewable energy projects. Government could pay a useful role in promoting renewable energy technologies by initiating surveys and studies to establish their potential in both urban and rural areas. Fig. 2 shows the major considerations for developing renewable energy technologies, as modified from Ref. [14].

As existing energy utilities often play a key role in determining the adoption and contribution of renewable energy technologies, the utility structure and the strategy for integrating renewables should be reviewed and studied. Utility regulations should be framed to reflect the varying costs over the networks, increase competitiveness and facilitate the access of independent renewable energy production. A major challenge for renewables is to get them into a reliable market at a price which is competitive with energy derived from fossil fuel, without disrupting local economies. Since the use of renewable energy often involves awareness of perceived needs and sometimes a change of lifestyle and design, it is essential to develop effective information exchange, education and training programs. Human resources knowledgeable in renewable energy technologies should be strengthened by establishing education and training programs. Energy research and development and

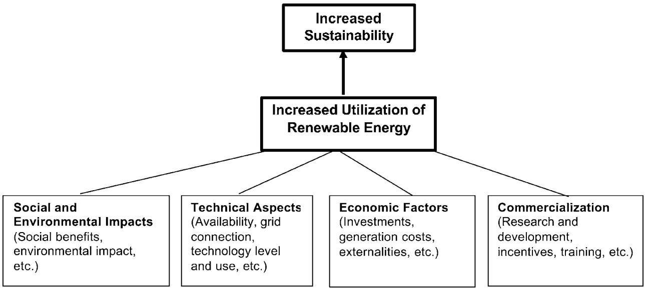

Fig. 2. Illustration the major considerations involved in the development of renewable energy technologies for sustainable development (modified from Ref. [14]).

demonstration projects should be encouraged to improve information and raise public awareness. The technology transfer and development process should be institutionalized through international exchanges and networking.

To overcome obstacles in initial implementation, programs should be designed to stimulate a renewable energy market so that options can be exploited by industries as soon as they become cost-effective. Financial incentives should be provided to reduce up-front investment commitments and to encourage design innovation.

4. Tools for environmental impact and sustainability

An energy system is normally designed to work under different conditions to meet different expectations (e.g., load, environment and social expectations). Life cycle assessment (LCA) can be applied to help design an energy system and its subsystems to meet sustainability criteria through every stage of the life cycle. LCA, as an environmental accounting tool, is very important.

Table 2 lists some available environmental tools, and detailed descriptions of each tool follow [15,16,17]:

- *Life cycle assessment* (LCA): LCA is an analytical tool used to assess the environmental burden of products at the various stages in a product's life cycle. In other words, the LCA examines such products "from cradle-to-grave". The term "product" is used in this context to mean both physical goods as well as services.

Table 2
Selected methods and tools for environmental assessment and improvement

Risk assessment	Environmental tools	Thermodynamic tools	Sustainability tools
	• Environmental performance indicators • Environmental impact assessment • Ecological footprints	• Exergy analysis • Material flux analysis	• Life cycle assessment • Sustainable process index

- *Environmental impact assessment* (EIA): EIA is an environmental tool used in assessing the potential environmental impact of a proposed activity. The derived information can assist in making a decision on whether or not the proposed activity will pose any adverse environmental impacts. The EIA process assesses the level of impacts and provides recommendations to minimize such impacts on the environment.
- *Ecological footprints*: Ecological footprints analysis is an accounting tool enabling the estimation of resource consumption and waste assimilation requirements of a defined human population or economy in terms of corresponding productive land use.
- *Sustainable process index* (SPI): SPI is a means of measuring the sustainability of a process producing goods. The unit of measure is m^2 of land. It is calculated from total land area required to provide raw materials, process energy (solar derived), infrastructure and production facility, and disposal of wastes.
- *Material flux analysis* (MFA): MFA is a materials accounting tool that can be used to track the movement of elements of concern through a specified system boundary. The tool can be adapted further to perform a comparative study of alternatives for achieving environmentally sound options.
- *Risk assessment*: Risk assessment can estimate the likelihood of potential impacts and the degree of uncertainty in both the impact and the likelihood it will occur. Once management has been informed about the level of risk involved in an activity, the decision of whether such a risk is acceptable can be subsequently made.
- *Exergy analysis*: Exergy is the quality of a flow of energy or matter that represents the useful part of the energy or matter. The conversion of energy in a process usually is driven by the consumption of energy quality. It is found that using the exergy concept to estimate the consumption of physical resources can improve the quality of the data necessary for LCA.

4.1. Ecologically and economically conscious process engineering

Numerous efforts have been trying to develop and promote ecologically and economically sustainable engineering (e.g., an example is available at Ohio State University [18]). When applying ecologically and economically sustainable engineering, industrial and ecological systems are treated as networks of energy flows.

Ecosystems convert sunlight to natural resources, while industrial systems convert natural resources to economic goods and services. Thus, all products and services are transformed and stored forms of solar energy. The energy flowchart for a typical industrial system that includes ecological and economic inputs is shown in Fig. 3. Traditional economic analysis only accounts for economic inputs, and outputs, since industry does not pay money to nature for its products and services. LCA focuses mainly on the waste streams, and their impact, while systems ecology ignores waste and its impact. Fig. 3 can be used for assessing the economic and environmental viability of products and processes.

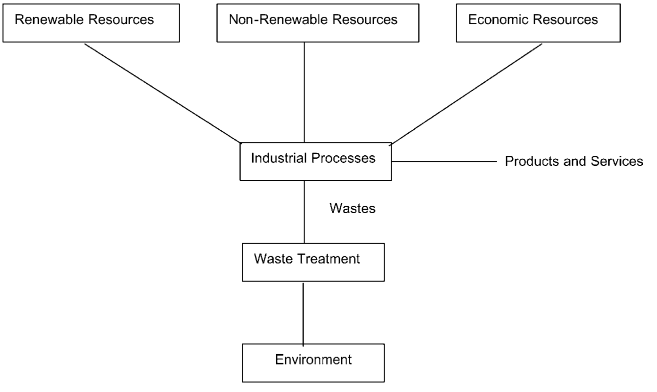

Fig. 3. An energy flow diagram for a typical industrial system that includes ecological and economic inputs (modified from Ref. [18]).

The thermodynamic approach for LCA and design accounts for economic and ecological inputs and services, and the impact of emissions. This approach is related to exergy and emergy analyses. Exergy analysis is popular for improving the thermodynamic efficiency of industrial processes. However, it ignores ecological inputs and the impact of emissions. These shortcomings of exergy analysis have been overcome by combining it with life cycle impact assessment and emergy analysis. Emergy analysis is a popular approach for analyzing and modeling ecosystems. The resulting approach bridges systems ecology and systems engineering. Applications of this approach to LCA and process design are being developed.

5. Sustainable development and thermodynamic principles

Thermodynamic principles can be used to assess, design and improve energy and other systems, and to better understand environmental impact and sustainability issues. For the broadest understanding, all thermodynamic principles must be used, not just those pertaining to energy. Thus, many researchers feel that an understanding and appreciation of exergy, as defined earlier, is essential to discussions of sustainable development.

Beyond individual behavior, we should think collectively about how society meets its energy needs, including decisions about energy resource selection, efficiency and the role of renewable energy sources such as wind and solar.

An inexpensive and stable energy supply is a prerequisite for social and economic development, in households as well as at the national level. Indeed, energy is essential to human welfare and quality of life. However, energy production and consumption generate significant environmental problems (at global, regional and local levels) that can have serious consequences and even put at risk the long-term sustainability of the planet's ecosystems. The relationship between energy consumption and production and sustainability is, therefore, complex [1].

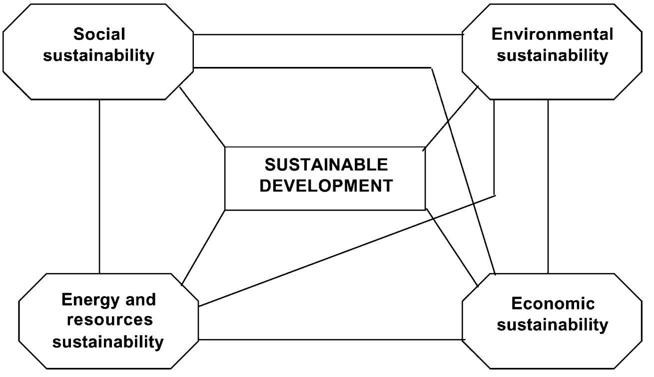

Fig. 4. Factors impacting sustainable development, and their interdependences.

We consider sustainable development here to involve four key factors, as shown in Fig. 4: environmental, economic, social and resource/energy sustainability. The connections in Fig. 4 illustrate that these factors are interrelated.

5.1. Exergy and the environment

Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. From an exergy viewpoint, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumption).

A deeper understanding of the relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting changes in the environment, and help researchers deal better with environmental damage.

The second law of thermodynamics is instrumental in providing insights into environmental impact. The most appropriate link between the second law and environmental impact has been suggested to be exergy, in part because it is a measure of the departure of the state of a system from that of the environment. The magnitude of the exergy of a system depends on the states of both the system and the environment. This departure is zero only when the system is in equilibrium with its environment. The authors have discussed this concept extensively previously [6,10].

Many have begun to investigate the links between exergy and the environment [6,19–22].

5.2. Exergy and sustainability

Mass and energy balances are normally evaluated prior to performing an exergy analysis. The energy information quantifies only the energy transfers and conversions in a system or process, whereas the exergy analysis, since exergy is a measure of the quality of energy, quantifies the degradation of energy or material in the

system. Exergy is conserved only for reversible or ideal processes. Exergy analysis is based on the combination of the first and second law of thermodynamics, and can pinpoint the losses of quality, or work potential, in a system. Exergy analysis is consequently linked to sustainability because in increasing the sustainability of energy use, we must be concerned not only with loss of energy, but also loss of energy quality (or exergy).

One great advantage of exergy analysis over energy analysis is that the exergy content of a process stream is a better valuation of the stream than the energy content, since the exergy indicates the fraction of energy that is likely useful and thus utilizable. This observation applies equally on the component level, the process level and the life cycle level. Application of exergy analysis to a component, process or sector can lead to insights in how to improve the sustainability of the activities comprising the system by reducing exergy losses.

Sustainable development requires not just that sustainable energy resources be used, but that the resources be used efficiently. The authors and others feel that exergy methods can be used to evaluate and improve efficiency and thus to improve sustainability. Since energy can never be "lost" as it is conserved according to the first law of thermodynamics, while exergy can be lost due to internal irreversibilities, this study suggests that exergy losses which represent potential not used, particularly from the use of non-renewable energy forms, should be minimized when striving for sustainable development.

Furthermore, this study shows that some environmental effects associated with emissions and resource depletion can be expressed based on physical principles in terms of an exergy-based indicator. It may be possible to generalize this indicator to cover a comprehensive range of environmental effects, and research in line with that objective is ongoing.

Combining exergy analysis with a LCA can provide both an unambiguous understanding of the consumption activities within the life cycle of a product of process and insights into potential exergy savings at the process and system levels. In many cases, these perspectives are not available through conventional energy analysis.

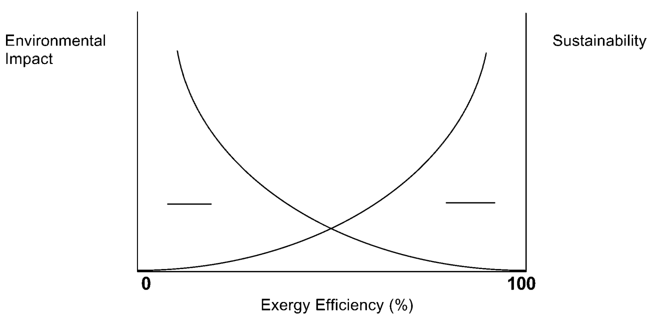

Fig. 5. Qualitative illustration of the relations between the environmental impact and sustainability of a process, and its exergy efficiency.

The relation between exergy, sustainability and environmental impact is illustrated in Fig. 5. There, sustainability is seen to increase and environmental impact to decrease as the exergy efficiency of a process increases. The two limiting efficiency cases in Fig. 5 are significant:

- As exergy efficiency approaches 100%, the environmental impact associated with process operation approaches zero, since exergy is only converted from one form to another without loss (either through internal consumption or waste emissions). Also sustainability approaches infinity because the process approaches reversibility.
- As exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources (fuel ores, steam, etc.) are used but nothing is accomplished. Also, environmental impact approaches infinity because, to provide a fixed service, an ever increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes are emitted.

Although this work discusses the benefits of using thermodynamic principles, especially exergy, to assess the sustainability and environmental impact of energy systems, this area of work is relatively new. Further research is needed to ascertain a better understanding of the potential role of exergy in such a comprehensive perspective. This includes the need for research to (1) better define the role of exergy in environmental impact and design, (2) identify how exergy can be better used as an indicator of potential environmental impact, and (3) develop holistic exergy-based methods that simultaneously account for technical, economic, environmental and other factors.

5.3. *Exergy as a common sustainability quantifier for process factors*

Exergy has several qualities that make it suitable as a common quantifier of the sustainability of a process [22]:

- Exergy is an extensive property whose value is uniquely determined by the reference-state parameters (of both the system and the reference environment).
- If a flow undergoes any combination of work, heat and chemical interactions with other systems, the change in its exergy expresses not only the *quantity* of the energetic exchanges but also the *quality*.
- Provided a chemical reference state is selected that is reflective of the actual typical chemical environment on Earth, the chemical portion of the exergy of a substance can be evaluated. The exergy of a substance such as a mineral ore or of a fossil fuel is known when the composition and the thermodynamic conditions of the substance and the environment at the extraction site are known. The chemical exergy of a substance is zero when it is in equilibrium with the environment, and increases as its state deviates from the environment state. For a mineral, for example, the exergy of the raw ore is either zero (if the ore is of

the same composition as the environmental material) or higher if the ore is somewhat concentrated or purified.

- The *value* of a product of a process, expressed in terms of "resource use consumption", may be obtained by adding to the exergy of the original inputs all the contributions due to the different streams that were used in the process.
- If a process effluent stream is required to have no impact on the environment, the stream must be brought to a state of thermodynamic equilibrium with the reference state before being discharged into the environment. The minimum amount of work required to perform this task is by definition the exergy of the stream. For this reason, many suggest that the exergy of an effluent is a correct measure of its potential environmental cost.

Some researchers (e.g., [22]) propose that an "invested exergy" value be attached to a process product, defined as the sum of the cumulative exergy content of the product and of the "recycling exergy" necessary to allow the process to have zero impact on the environment. They further suggest the following, for any process:

- A proper portion of the invested exergy plus the exergy of a stream under consideration can be assigned to the stream, thereby allowing the process to be "charged" with the physical and invested exergy of its effluents.
- If a feasible formulation exists to convert the remaining "non-energetic externalities" (labour and capital) into exergetic terms, their equivalent input in any process could be summed to the exergy and invested exergy of each stream. The exergy flow equivalent to labour can perhaps be estimated by assigning a resource value to the work hour, computed as the ratio of the yearly total exergetic input in a society or region to the total number of work hours generated in the same period of time. Similarly, the exergy flow equivalent to a capital flow can perhaps be estimated by assigning a resource value to the monetary unit, computed as the ratio between the yearly total exergetic input in a society or region and the total monetary circulation (perhaps in terms of gross domestic product, or total retail sales, or a different financial measure) in the same period of time.

6. Concluding remarks

The benefits have been demonstrated of using the principles of thermodynamics via exergy to evaluate energy systems and technologies as well as environmental impact. Thus, thermodynamic principles, particularly the concepts encompassing exergy, can be seen to have a significant role to play in evaluating energy and environmental technologies. The following concluding remarks, which will likely be useful to scientists and engineers as well as decision and policy makers, can be drawn from this study:

- Moving towards sustainable development requires that environmental problems be resolved. These problems cover a continuously growing range of pollutants, hazards and types of ecosystem degradation, and extend over ever wider areas.

Some of the most significant environmental problems are acid precipitation, stratospheric ozone depletion, and global climate change. The latter is potentially the most important.
- Sustainable development requires a sustainable supply of energy resources that, in the long term, is sustainably available at reasonable cost and can be utilized for all required tasks without causing negative societal impacts. Energy sources such as sunlight, wind and falling water are generally considered renewable and, therefore, sustainable over the relatively long term.
- Assessments of the sustainability of processes and systems, and efforts to improve sustainability, should be based in part upon thermodynamic principles, and especially the insights revealed through exergy analysis.
- For societies to attain or try to attain sustainable development, effort should be devoted to developing renewable energy resources and technologies. Renewable energy utilization can provide an important solution to current environmental problems. Advanced renewable energy technologies can provide environmentally responsible alternatives to conventional energy systems, as well as more flexibility and decentralization.
- To realize the energy, exergy, economic and environmental benefits of renewable energy sources, an integrated set of activities should be conducted including research and development, technology assessment, standards development and technology transfer. These can be aimed at improving efficiency, facilitating the substitution of renewable energy and other environmentally benign energy currencies for more harmful ones, and improving the performance characteristics of renewable energy technologies.

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